Breaking vertical boundaries
The spatial logics and underground potential of San Antonio, Texas

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Abstract:

For the past century, the urban underground has been developed piecemeal out of necessity rather than as the object of a long-term planning effort. The underground contains not only potential usable space, but also raw materials, groundwater and geothermal energy sources from which urban areas benefit to varying degrees. Questioning the role of underground resources in future urbanization throws into relief the norms and procedures that are poorly adapted to a volumetric planning of the city, yet offers a new realm of possibilities for the mixing and intensification of land uses and improving accessibility, while preserving surface green spaces. This paper presents the theoretical and practical issues at hand and then builds upon a methodological framework developed by the Deep City project at the EPFL in Switzerland, taking San Antonio, Texas, as a case study. The preliminary results of the urban and hydrogeological analyses illustrate the challenge of integrating a reflection about the third dimension into an already complex urban context.

From resources to needs: a change in paradigm

From the end of the nineteenth century and throughout the twentieth, the urban underground was the canvas of engineered flows. The mechanical metaphors used in addressing the city as a living organism in the early 1900s saw the underground as the city's vital support system (Shane, 2005). French engineer Eugène Hénard envisioned a Paris street of the future where underground trains moved people and automated trolley systems transported and delivered goods to the basements of buildings—in order to liberate the surface of unwanted congestion and restore light and air to city dwellers (Hénard, 1982). In North America, the idea at the time that poor ventilation and darkness (particularly in apartment buildings) led to antisocial behavior resulted in the zoning laws that have created the low density post war development observable in nearly all American cities today (Talen, 2012). In such a context, going underground was a necessary evil—simply a way for people and goods to move from point A to point B.

The popularity among engineers and architects of mechanized ventilation and electrical lighting in the 1960s and 70s made large un-fenestrated indoor spaces possible. Underground transport could be not only about movement but also shopping and entertainment. Architects I.M. Pei and Henry Cobb's Place Ville-Marie office complex in Montreal placed half of its floor area underground, guided by urban planner Vincent Ponte's futurist-inspired vision for a multi-level city (Besner, 2000). Today, Montreal's not partially underground Indoor City allows office workers, residents and tourists to circulate through cultural and commercial spaces without having to venture outside—a benefit most appreciated during the winter (Boisvert, 2011). Climate is often an impetus for underground development, of which Montreal, Toronto, Helsinki, Dallas, and Singapore are only a couple examples (Blunier, 2009).

If the form taken by the urban underground has reflected the overarching ideology of the time, the discourse at the beginning of the twenty-first century is attempting to reconcile the underground heritage of previous eras with contemporary debates on sustainable urban forms and lifestyles. There has been a persistent, but little heeded, call for coordinated surface and subsurface planning for a century now (Barles & Guillerme, 1995; International Tunnelling and Underground Space Association, 2012; Utudjian, 1952), which seems to come and go with the rhythms of economic growth and stagnation. The demographic booms that brought about increased built densities and urban transportation systems for the West have shifted to Asia and Africa (United Nations Human Settlements Programme, 2013). North American and European cities are now either shrinking or faced with single digit growth projections. In this context, one could ask whether or not and where the underground should be an important object of urban planning today.

The answer to this question comes from at least two, sometimes conflicting, fronts. On the one hand, improvements in construction technologies in the past several decades have made it easier and cheaper to build in less than ideal underground conditions. Organizations such as the International Tunnelling and Underground Space Association (ITA) and the Associated Centers for Urban Underground Space (ACUUS) have become important actors in promoting the benefits of underground use for all cities. On the other, a strain of thought harking back to Ian McHarg's *Design with Nature* (McHarg, 1969) has emphasized the important symbiosis between artificial and natural systems, reminding us that human settlement occurs near resource-rich areas. Exploitation risks their destruction and the endangering of existing plant and animal ecosystems.

The need to plan the underground today arises from the paradigmatic differences within which these two forms of discourse operate. If designing with nature is more about responding to contextually derived underground conditions, technological progress tends to find such conditions negligible (in effect, designing against nature) as long as the necessary capital is present. Recent scientific literature and reports from various international organizations (such as the ITA and ACUUS) view underground development as a way to preserve surface land while increasing buildable opportunity beneath it, improve urban connectivity in densely built areas, counter urban sprawl and increase land use intensity through the vertical overlapping of functions (Chen, Zhang, & Guo, 2011; Durmisevic, 1999; Goel, Singh, & Zhao, 2012; International Tunnelling and Underground Space Association, 2012; Monnikhof, Edelenbos, van der Hoeven, & van der Krogt, 1999; Zhang, Chen, & Yang, 2011; Zhao, 2011). Best practices from various urban contexts serve to illustrate the feasibility and potential success of such options. The specific social, economic and environmental constraints of the local context are obstacles to overcome.

The feasibility and long term impact of underground development strongly depends on the urban hydrogeological context. The relationship of a city to its underground is related both to the resources available (including potential space, groundwater, minerals and geothermal heating and cooling opportunities) and to the conflicts and synergies between them (Aurèle Parriaux, Blunier, Maire, Dekkil, & Tacher, 2010). Mexico City, for instance, has overexploited its aquifer to the point that caverns previously filled with groundwater are sinking and in some places collapsing. In Paris and Tokyo, a decrease in extraction of groundwater has led to a rise in water level, posing problems of water damage to underground infrastructures constructed for previous levels (Blunier, 2009). Success stories include Montreal and Helsinki, where the lack of an important aquifer (as well as a stable bedrock) (Blunier, 2009) have allowed both cities to place a significant number of non-transportation spaces underground, from shopping malls and cinemas in Montreal (Boisvert, 2011) to sports arenas and water filtration facilities in Helsinki, which has reused the excavated material for infill (Vähäaho, 2009).

The potential synergies and conflicts between underground resources and their exploitation suggest that before a city can evaluate whether or not planning is necessary, it needs to know for what and with what to plan. That is, rather than plan an underground transportation system that it may not need in the short term, an initial investigation would first document hydrogeological and urban potential and then identify the locations where underground infrastructure could be placed if it were to prove to be a viable option. This requires a change in paradigm, by which resource potential comes before needs and where underground development serves to maximize synergies and minimize conflicts (Aurèle Parriaux et al., 2010). The first step in this paradigm change is a procedural one and the next section will present a methodology developed in Switzerland to evaluate the potential of a city's underground resources.

The Deep City Methodology and beyond

The Deep City project at the *École polytechnique fédérale de Lausanne* (EPFL) in Switzerland has spent the last several years developing and testing a method to evaluate four main urban underground resources: groundwater, space, minerals and geothermal energy. Evaluation relies on mostly hydrogeological data acquired from diverse sources. In order to facilitate the consultation of such information by non-specialists, the Engineering and Environmental Geology lab (GEOLEP) at the EPFL developed a series of geological classifications (*geo-types*) that summarize the overall geotechnical behavior of a family of geological formations (Blunier, 2009). Because formations often differ only in name from region to region, translation into types seeks to standardize terminology and allow for initial hypotheses about geotechnical characteristics to be formed before local site specific investigations are carried out. The geo-types are represented two-dimensionally in GIS and modelled three-dimensionally where the general depth of formations is known or is able to be deduced from geological sections (Blunier, 2009).

The potential of each resource is evaluated according to different sets of criteria. Groundwater potential depends principally on the variations in height of the aquifer and its relative salinity (to get an idea about whether or not it is potable). Geothermal potential relies on the thermal conductivity of the geology, which in turn is a function of its degree of saturation. The evaluation of mineral resources depends on the granularity of the formation (often highly site-specific) and the potential for marketization (often based on current uses by individuals or local industry) (Parriaux, 2009). Space potential is determined by the quality of the geological formation (including its estimated level of saturation) as well as the ease of extraction (Blunier, 2009). Existing legal frameworks concerning flood areas or aquifer recharge zones are also an important reference (Maire, 2011).

A quantification of development potential is carried out using the Analytical Hierarchy Process (Saaty, 1980). Rather than rate, for example, the geothermal potential of each geo-type linearly (e.g. 1-10), they are compared pairwise according to linguistic qualifiers (e.g., ‘no preference between A and B’, ‘A is moderately preferable to B’, ‘A is very preferable to B’, etc.) in order to develop a relative level of priority. Ideally these pairwise comparisons are carried out by a series of local experts on the different resources and the legal conditions of their use. Different development scenarios can then be developed using Order Weighted Average (combined with AHP by (Boroushaki & Malczewski, 2008)) whereby the level of priority of the development of each resource is weighted according to a series of objectives (e.g. geothermal use over drinking water or space). The team can then map the results in GIS and compare and discuss the alternatives as part of an overall decision-making process.

The process of investigating and weighting geo-types distills certain economic concerns such as the market value of minerals or the cost of extraction, but does not account for the variations in land value that depend more on the existing distribution of urban uses and morphology than on geological conditions. Although intuitively the underground option for a project is more expensive, this depends on a variety of factors that can be investigated early on in the planning process. Simulation by the Deep City project of construction costs (including in difficult and easier geological conditions) and operation costs for three different surface and subsurface commercial building scenarios in Switzerland concluded that the underground option is more likely to be economically feasible when the project is both above and below ground and is situated in locations where land value is higher than average, which are often highly frequented urban areas (Maire, 2011). This suggests that underground development should be oriented first and foremost towards areas of a city where demand for land is high and where there is an interest in building not only up, but also down.

The Deep City Method in its current stage sets the foundation for a three-dimensional planning of the city that combines the hydrogeological conditions of the subsurface with the economic and spatial characteristics of the existing urban tissue. But how can the planning process translate development potential into normative instruments to guide city development? Once the method has identified an area of town with high underground development potential, how do we pinpoint the specific location for a future project in the existing urban, suburban or even rural tissue? In order to attempt to answer these questions, the next section will return to the literature on design and legal planning issues facing underground development.

Centers of attraction: spatial logics for decision-making

A method to identify locations for integrating future underground projects into the existing urban fabric faces the challenge of the vast formal heterogeneity of cities and urbanized territories. Classical city models based on the central place and location theories of Christaller, Lösch and Thünen are criticized for describing the city in overly mechanistic and reductionist terms as simple systems, while the Marxist and the Humanistic cities of figures like Castells and Tuan, respectively, tend to address the city in its political and social-economic—rather than spatial—dimensions (Portugali, 2011). Situated in between these two is a discourse that parallels Jane Jacob's observation that what makes cities work emerges from the seeming chaos of daily city life (Jacobs, 1961) and reflects Christopher Alexander and colleagues' (Alexander, Ishikawa, & Silverstein, 1977) identification of a variety of spatial patterns that support different human activities.

Urban form emerges from the movement generated by groups of people between different places. It also structures this movement, so that certain streets are more likely to be traversed than others, and is structured by it, so that destinations like shops or meeting places situate themselves on or nearby important axes, thereby taking advantage of a concentration of potential visitors (Hillier & Hanson, 1984). Space Syntax Limited at the University College London, using graph theory accessibility measures of street networks, has found that the importance of urban centers is multiscalar—a street or group of streets may be an important destination (mathematically understood as a closeness measure, *integration*) or through-street (a choice metric, *betweenness*) for the surrounding neighborhood, but might be more likely to be completely bypassed by people travelling across town. These metrics have been found to correlate well with traffic data (Hillier & Iida, 2005) and can be used to compare general trends in the global and local structure of different cities (Hillier, Yang, & Turner, 2012).

A limitation of using the street network as the unit of analysis is that not all streets are equal and one street with a high potential to attract movement may actually be a (perhaps poorly planned) residential street while a commercial center may in reality attract a lot of people, but be relatively segregated in the urban fabric. Although Space Syntax can bring to light these discrepancies in order to question them, analysis of buildings or parcels weighted according to a set of characteristics provides a more realistic picture of urban form. A choice (*betweenness*) metric and closeness-like metric (*reach*) were found to describe well the location and agglomeration behaviors of commercial establishments in the Boston area when weights like built volume and number of places of employment or residents were tested at various metric radii (Sevtsuk, 2010). These metrics have since been packaged into the Urban Network Analysis Toolbox, a plug-in for ESRI's ArcGIS 10[1]. The ability to measure not only the impact of street configuration, but also variations in built form and the activities they house, allows a more complete picture that can be used to test the impact of different design options.

What do measures of street networks and urban form have to do with locating and configuring underground projects? Indeed, not all underground infrastructures (e.g. water treatment plants, food storage or urban mines) benefit from being along highly frequented axes or hope to attract a large number of visitors. Where issues related to connectivity are limited, such measures would only be relevant locally, such as where access points to the facilities would occur and their relationship to the existing street network and adjacent activities. In Helsinki, a water treatment plant is located in a rock cavern deep beneath a residential neighborhood practically unbeknownst to the residents (Vähäaho, 2009).

Underground infrastructures have the greatest potential impact on the movement potential created by the urban morphology where they form complex transport and pedestrian systems beneath the surface. They take advantage of the flow of people through them, which is why they are often connected to office spaces, transit stations or parking facilities. The underground flows are dependent as well on surface flows, suggesting that their success depends on a delicate balance between their ability to benefit from the attractiveness of surface destinations, without draining potential visitors from street level (Zacharias, 2000). The graph theory metrics can aid in estimating in advance the impact of future underground development, identifying from the global to local scale locations of interest for projects that seek to be next to or far from existing flows of people. Their contribution to the design process can only go so far. The following section will ask whether underground planning ought to seek to

[1] http://cityform.mit.edu/projects/urban-network-analysis.html

develop finer grained design guidelines and whether certain aspects ought not to be left to chance.

Connecting legal and design issues

Legal and design issues are recurring themes in the literature on the underground. The former appears to seek to facilitate the emergence and process of underground projects, assuming that the appropriate laws will encourage the growth of development. The latter wants to inform the design process of these projects with best practices backed up by empirical evidence, with the idea that there exist common spatial criteria that are applicable to a variety of different project types. A brief overview of these issues reveals that they may be best addressed together, rather than separately.

According to a survey conducted of eight countries by a working group of the International Tunnelling Association (Nordmark, 2000), one of the main obstacles to underground development is the ambiguity related to the depth of the rights of surface property owners. In some countries ownership extends to the center of the earth, while for others is extends to about six meters or to a depth of reasonable use for the activities of the surface owner. A more in-depth analysis of the Swiss legal context performed by the Deep City Project (Maire, 2011) found that once laws governing aquifer protection, geothermal use and the various legal devices like easements were factored in, the depth of property ownership becomes practically a non-issue. Furthermore, countries that have implemented three-dimensional property and cadaster systems have not found the demand for underground projects increase (Paulsson, 2013; Stoter, 2004). These systems facilitate the realization of projects that stem from an existing demand, but they will not alone spur specific underground development envisioned by a city.

Design guidelines and best practices for underground spaces have been produced and investigated since at least the 1980s. While some even go into recommending colors and patterns (Carmody, 1993), most develop formal and configurational principles for reducing the feeling of being underground either by expanding the visual field (von Meiss, 2004), using visual cues to facilitate way-finding both for finding a destination and in cases of egress (Durmisevic, 1999), or easing the transition into the underground from the surface by connecting through existing buildings or horizontally through sloping topography (Bélanger, 2007; Carmody, 1993;

Golany & Ojima, 1996). Results from surveys conducted in the Netherlands and Canada suggest that in underground transportation and pedestrian spaces the presence of others (without over-crowding) and the minimization of dead-end corridors and hidden areas contribute to a sense of security and facilitate movement (Boisvert, 2011; Durmisevic, 2002; Zacharias, 2001).

The resemblance of these design concerns to urban streets, particularly when taking for example the extensive networks of Toronto and Montreal as an example, is not arbitrary. In North America in particular, street design is being increasingly governed by simplified sets of form-based rules governing relationships between urban elements, as a complement to or substitution for existing use-oriented zoning (Talen, 2012). A similar strategy for the underground could be a way to merge design concerns with legal ones. Form-based codes develop volumetric and sectional design principles that ensure a certain continuity of form in the urban fabric (Parolek, Parolek, & Crawford, 2008). These rules are applied contextually along street axes and so would vary according to adjacent land uses or urban forms (Duany & Talen, 2002). Along with other legal instruments and without having to be overly prescriptive, they provide an interesting strategy for underground planning to be integrated with surface planning—to become, essentially, volumetric. The next section will illustrate current progress of an ongoing case study of the city of San Antonio, Texas, which seeks to test the Deep City method from geological and urban morphological potential to city planning.

San Antonio, Texas: case study preliminary results

Groundwater resources pose the greatest challenge to a city's relationship to its underground, particularly when they provide a significant source of drinking water (Blunier, 2009). Unlike geological materials (the exploitation of which has only a limited geographical impact) groundwater extraction or pollution have consequences that can reach a much larger scale (Morris et al., 2003). According to the World Hydrogeological Map (Struckmeier & Richts, 2008), at least 122 cities around the world with a population of greater than 1 million obtain at least 25% of their total water consumption from groundwater. Verifying each of these cities individually using information from local and national organizations, reveals that at least 50 rely on an urban aquifer for more than 50% of their drinking water (Figure 1). Several of these cities would provide an interesting amount of complexity to test and validate the Deep City method.

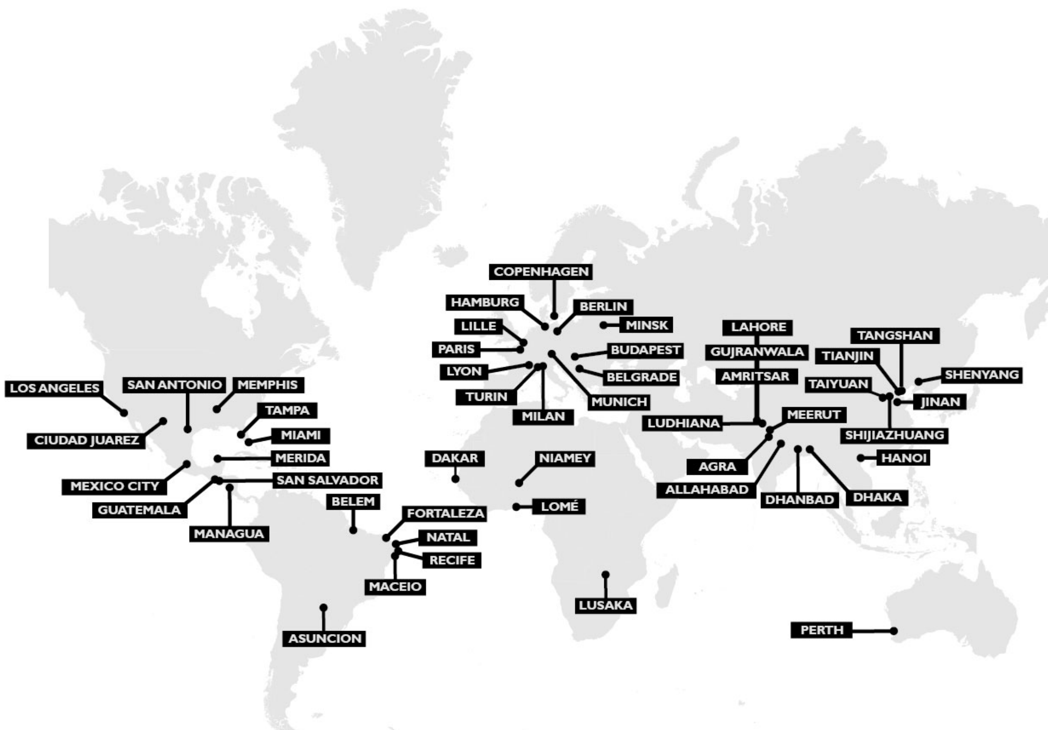


Figure 1. 50 world cities rely on an urban aquifer for more than 50% of their drinking water.

In addition to hydrogeological complexity, urban areas come with their own set of challenges. In North America, Western Europe, Japan and Oceania, cities are facing various environmental issues related to high levels of resource consumption, population decline and low density suburban sprawl (United Nations Human Settlements Programme, 2009). This latter is particularly pronounced in North American cities, where underground development would respond less to pressing land shortage than to climate issues, preservation concerns or radical compact urban development policies. As such, the North American context is particularly interesting. Whereas previous analyses of Geneva (Blunier, 2009) and Suzhou, China, (Li, 2013) were spurred by a desire for sustainable underground resource management combined with historic preservation of surface neighborhood character, the five North American case study candidates of Memphis (Tennessee), Miami (Florida), Los Angeles (California), San Antonio (Texas) and Tampa (Florida) offer a different context where surface space is abundant and existing underground urban spaces are limited. The author's participation in the 44th conference of the Urban Affairs Association in San Antonio in

2014 made it a good first test candidate for advancing the Deep City Method, before continuing with cities on other continents.

San Antonio, Texas, is located in Bexar County in south central Texas and is the seventh largest city in the United States with an urban area population in 2013 of 1.9 million on an urbanized area estimated at approximately 1546 square kilometers (597 mi^2). In comparison to cities of a similar population size, it is half the density of Hamburg (Germany), a third the density of Vienna (Austria) and less than a fourth the density of Minsk (Belarus) (Demographia, 2013). About 35% of the population lives within the highway 410 (Connally) loop and another 40% lives between 410 and the 1604 (Charles W. Anderson) loop (U.S. Census Bureau, 2010). Resident population densities are concentrated within the 410 loop and from the northwest to northeast areas between 410 and 1604 (Figure 2).

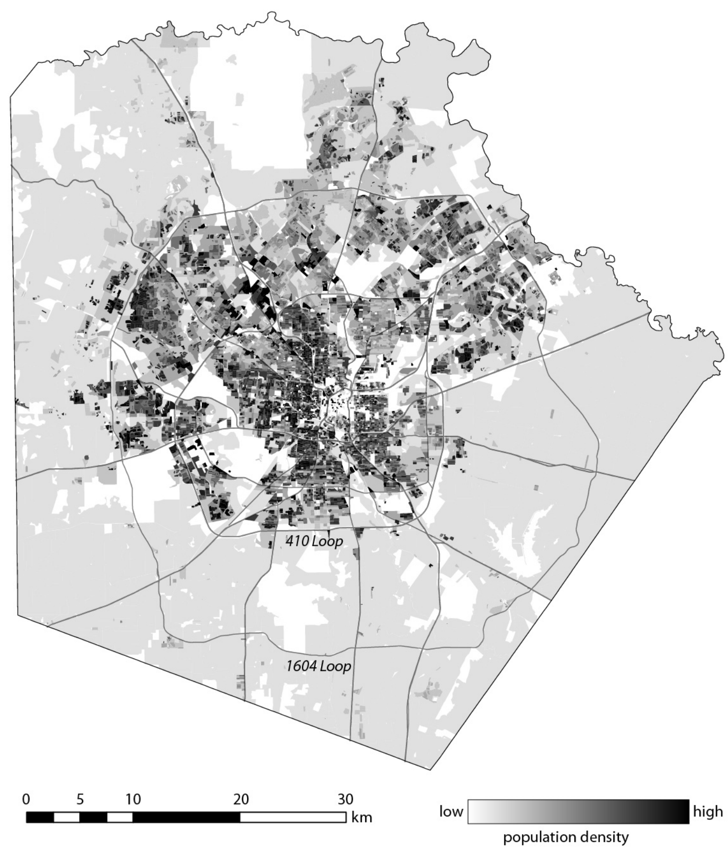


Figure 2. 35% of the population lives within Loop 410; 40% lives between 410 and 1604.

San Antonio is located on the Balcones Fault Zone, which explains the variety of geological strata exposed in the Bexar county area (Figure 3), with older limestone and granite in the Northwest and younger clay and sand in the southeast. The ease of building on the older strata may explain the greater concentration of resident population densities in the North: the clay soils in the south require additional measures to stabilize building foundations (Ewing, 2008). The Balcones Fault Zone contains the Edwards Aquifer, which crosses Bexar County from southeast to northeast, and is the primary water supply source for many residents of San Antonio and neighboring communities. The limit of the artesian zone to the south is determined by the presence of subsurface saline water, that threatens to enter and contaminate local wells if not monitored properly (Thomas, Stanton, & Lambert, 2012).

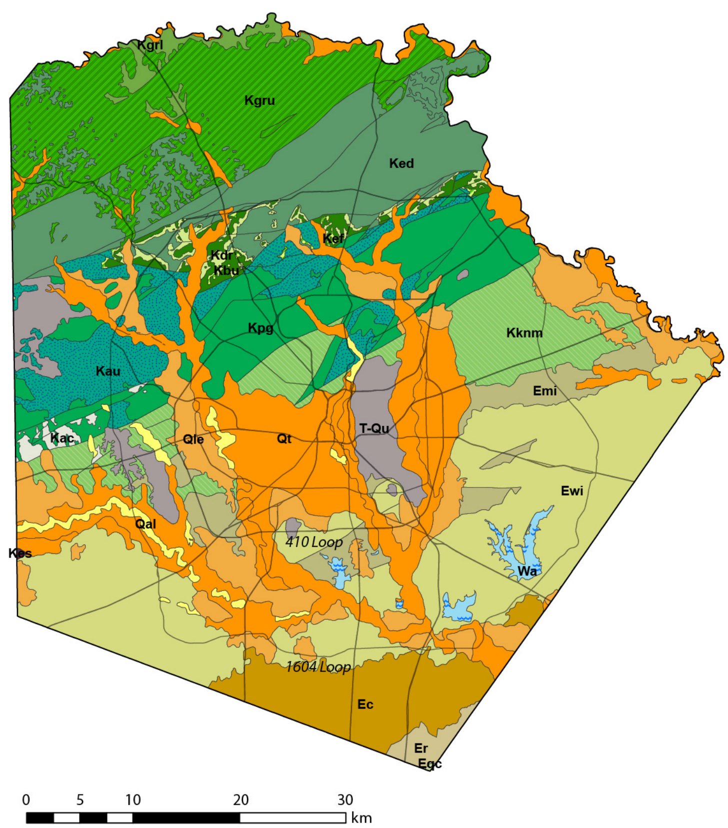


Figure 3. Bexar County's geology varies from hard limestone and chalk in the north to clay and sand in the south.

Descriptions of local geological formations accompanying the San Antonio Sheet of the Geologic Atlas of Texas (University of Texas at Austin, Bureau of Economic Geology, 1983) were referred to by the Deep City team in order to attempt a preliminary division into geo-types of the sixteen geological formations found within the San Antonio area. The analysis identified seven types, including a series of younger surface formations varying from 20 to 45 feet deep (APA and APT) following the alluvial plains of the Medina and San Antonio rivers and the Salado and Leon creeks, two limestone types (C and CS) situated around the northern sector of 1604 near the municipalities of Hollywood Park and Shavano Park, a hard chalk and limestone (MC) type found on either side of the C and CS formations and two clay (MGR) and sand (GR) geo-types found mostly in the southern half of the city from Lackland and Fort Sam Houston military bases to the municipalities of Somerset and Elmdendorf (Figure 4)

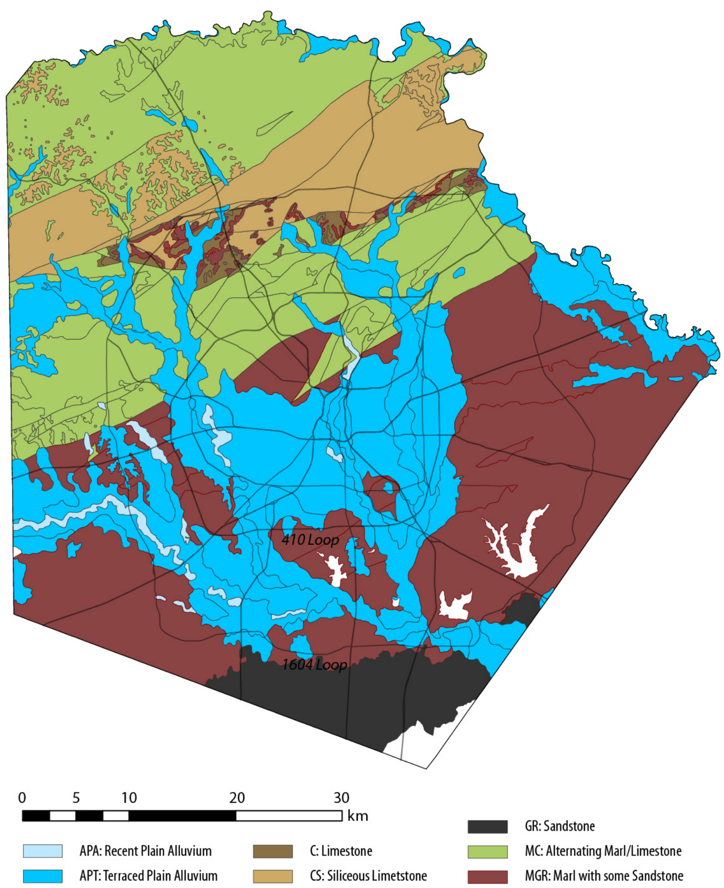


Figure 4. The sixteen geological formations can be classified into seven geotypes.

Further investigation of the resource potential of each geo-type using groundwater level (Texas Water Development Board, 2014), mineral resource locations (United States Geological Survey, 2014) and exploitation (Texas State Historical Association, Internet) and geothermal data (Blackwell & Richards, 2004) for the region permitted an initial attempt to calculate relative development potential. Even though the logic behind the pairwise comparisons remains to be verified with local experts, the analytical hierarchy process (Saaty, 1980) was conducted for the four resources. Space potential (Figure 5) is highest in the C and MC types due to the lower likelihood of containing water from the Edwards aquifer. Groundwater potential is highest in the Edwards formation (CS) and lowest in the clay and sand formations (MGR and GR) where only near-surface groundwater sources might be available (Figure 6). The ease of extraction and wide use for local construction of limestone give the MC and CS geo-types preference in terms of extraction and excavation (Figure 7). Due to the high thermal conductivity of the C, CS and GR types, the implementation of geothermal heating and cooling systems seems most promising to the north of the city and to the southern extremity of Bexar County (Figure 8).

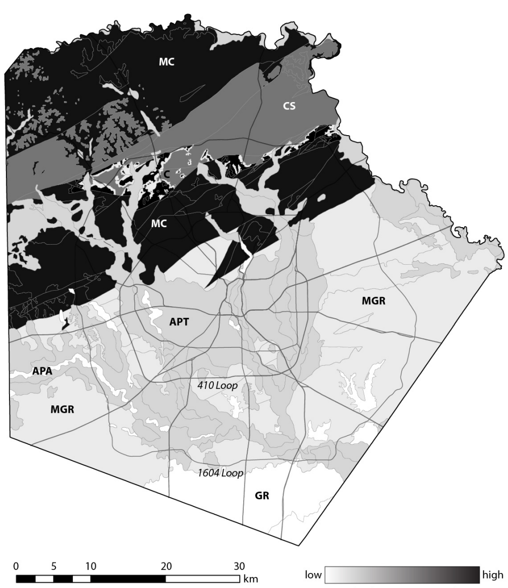


Figure 5. Underground space development potential

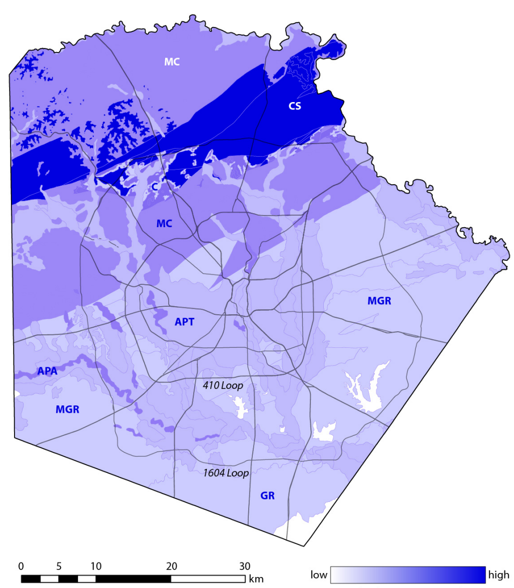
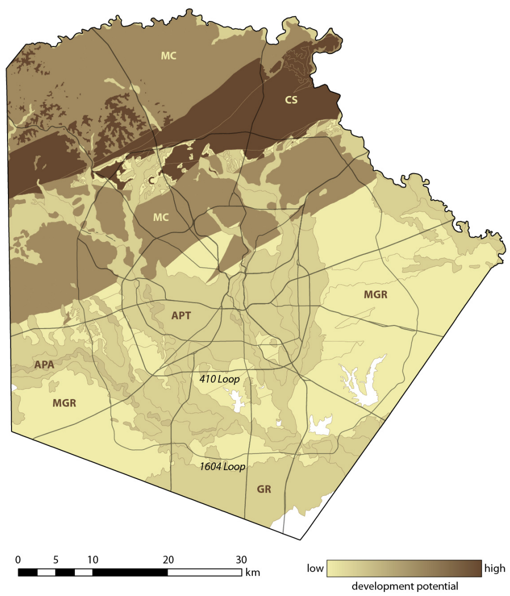


Figure 6. Groundwater development potential



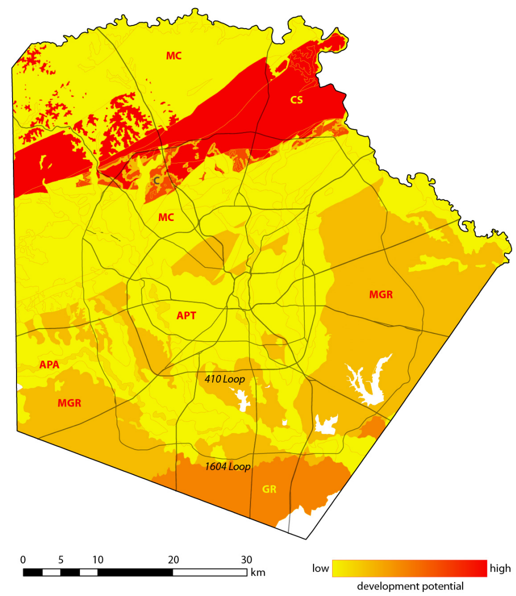


Figure 7. Mineral extraction potential **Figure 8.** Geothermal energy potential

Before speculating on what this potential may mean for underground development in San Antonio, several urban planning objectives illustrate what is currently on the boards. The *San Antonio 2020* visioning process conducted through a series of public forums and over 5000 surveys in 2010-2011 laid out the urban planning objectives for the city for the next ten years (Byrd, Rodriguez, & Weston, 2011). Some of these goals include increasing walkability and the number of pedestrian-oriented neighborhoods and multi-modal streets as well as concentrate development in already urbanized areas. The transportation plan for 2035 developed by VIA Metro Transit (Jacobs Engineering, 2011) identifies seven main corridors for future public transportation projects (Figure 9), through analysis of traffic and origin-destination data in addition to population and demographic forecasts. These corridors seek to link the main activity hubs of the city, while decreasing congestion on existing arteries.

Figure 9. Seven corridors are the focus of VIA Metro's transit plan for 2035 (Jacobs Engineering, 2011).

How do these corridors coincide with areas of high underground development potential? A test analysis of the urban street network and parcel metrics identified three corridors that overlap areas of the city where there is a high potential for underground space use: the bus rapid transit (BRT) Fredericksburg/Northwest line that follows Fredericksburg Rd from the new Westside Multimodal Transit Center in downtown to a northwestern portion of the 1604 loop; a portion of the South/West Connector BRT line that runs parallel to the Fredericksburg/Northwest line north of 410 and terminates at the South Texas Medical Center; and the northern portion of the North/South Central light rail (LRT) corridor that connects the airport to the downtown and traverses some of the densest areas of population and employment.

Normalized values for the choice (*betweenness*) and closeness (*integration*) least angular metric analyses calculated using Space Syntax's DepthMap software suggest that the Bexar county street network is characterized by a strong foreground network (the ring roads and radial arteries) and a rather weak background network (sections of the street grids or suburban developments). This means that it is easy to move around the city, but that a significant portion of the network is relatively inaccessible (perhaps segregated by the strong regional arteries) without making a large number of turns to get there, which has also been found to characterize cities like Las

Vegas, Kyoto and Beijing (Hillier et al., 2012). Looking at the arteries likely to harbor the greatest amount of movement in the sectors with the highest underground development potential highlights the San Pedro avenue corridor where the North/South Central LRT is slated to pass, Fredericksburg Road where the BRT Fredericksburg/Northwest line will run, Bandera Road running through the municipality of Leon Valley and at least four or five others.

The complexity of the analysis is significantly reduced if it considers only streets that risk channeling movement at a greater number of metric radii. This 'pervasive centrality' supposes that centrality pervades the urban grid at multiple scales in order to attract through- and to-movement for people travelling across town as well as from several blocks away (Hillier, 2009). As mentioned above, Space Syntax's use of street networks as the basic unit of analysis neglects differences in levels of street development. Because building information was not available for San Antonio, parcel data obtained from the Bexar County Appraisal District weighted according to land value was used as a proxy for potential built space. Because of computational limitations, parcels of the same state land use category were grouped together and assigned their total appraised value. The Urban Network Analysis Tool (Sevtsuk, 2010) for ArcGIS 10.2 measured the reach to surrounding parcel groups for each parcel group county-wide at metric radii equivalent to 5- (400 m), 10- (800 m), 15- (1200 m) and 20- (1600 m) walks, excluding roads off-limits to pedestrians (like highways or access ramps) (Figure 10).

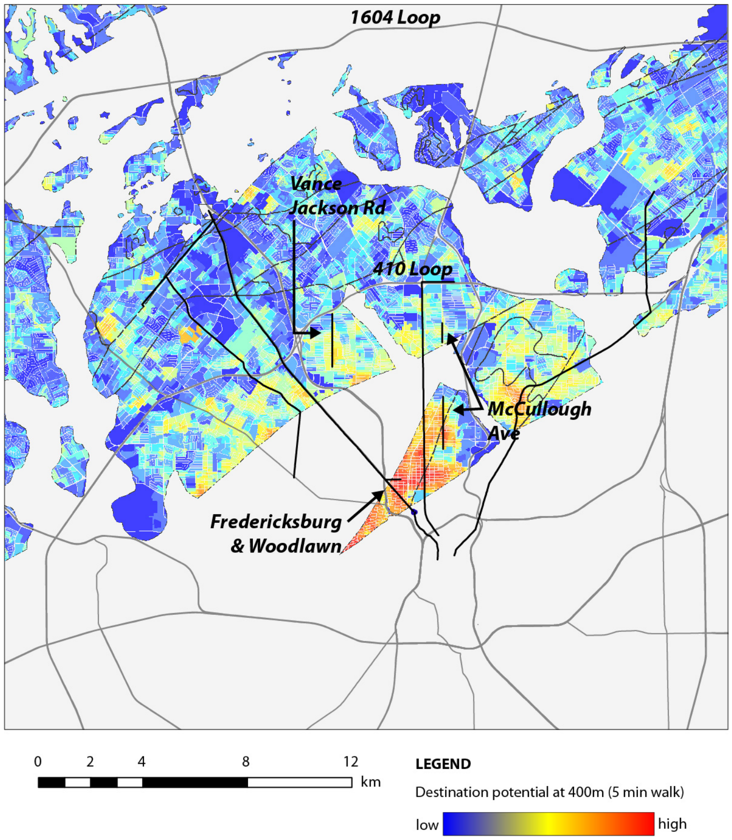


Figure 10. Several areas with a high destination and through-movement potetential are situated above potential underground development zones.

Investigation of pervasive centrality looked at both the combined metrics of multiple normalized choice radii (the whole network, 15 km, 10 km, 5.4 km, 3.2 km, 2 km, 1.6 km, 1.2 km, 800 m and 400 m) computed by Depthmap and the integration-like *reach* metrics of parcel groups at the radii mentioned above. Only four streets overlapping the area of high underground space development potential are situated in top 20% of normalized choice when measured with Depthmap and correspond to areas that are potentially walkable up to a 20 minute walk. McCullough drive and Hildebrand Avenue (Figure 11), south of East Olmos near the northern downtown neighborhood of Olmos Park seem to work together to draw movement from 15 kilometers to 400 meters away. McCullough is a commercial street situated amidst single and multi-family residential housing of two to three floors. Vance Jackson Road (Figure 12), where it runs north-south to the east of Balcones Heights also has the potential to attract through-movement from 800 meters up to 10 kilometers away. It is also a commercial street running through a residential neighborhood. Fredericksburg Road, to the east of interstate I-10 just north of downtown is the only portion of the Fredericksburg/Northwest corridor line where the street network and parcel measurements suggest that a five to 10 minute walking radius is imaginable. It is again a mostly commercial street flanked by residential neighborhoods.

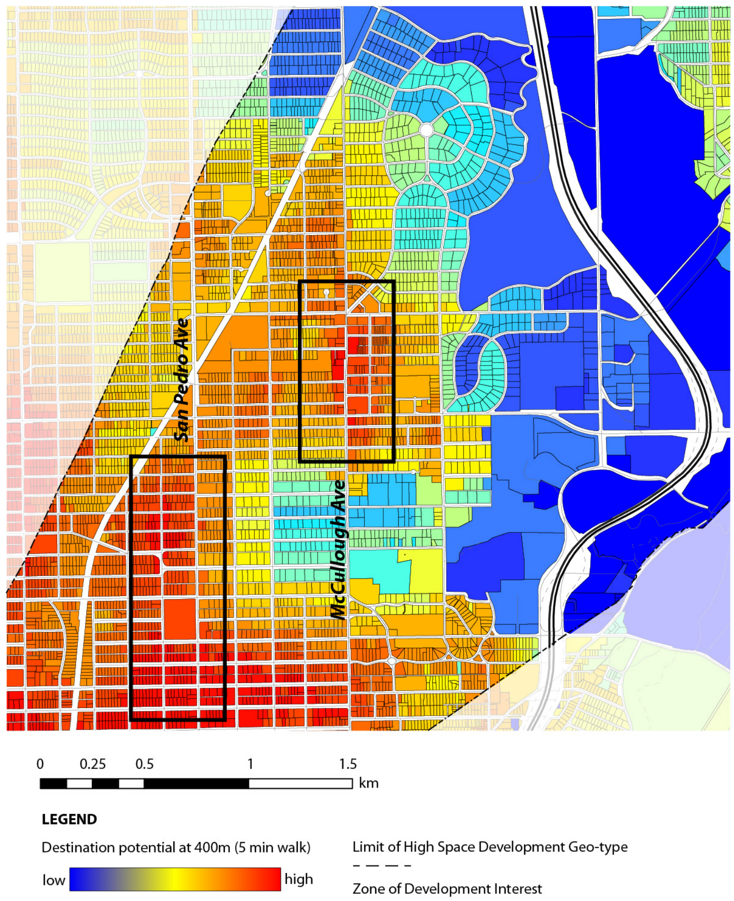


Figure 11. McCullough Avenue in Olmos Park

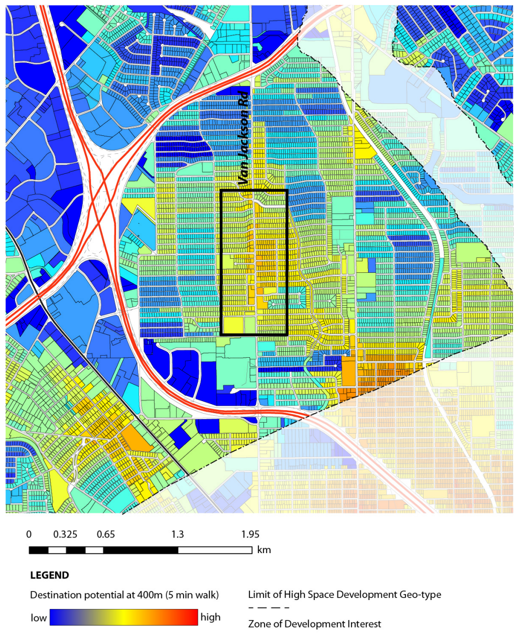


Figure 12. Vance Jackson Road to the east of Balcones Heights

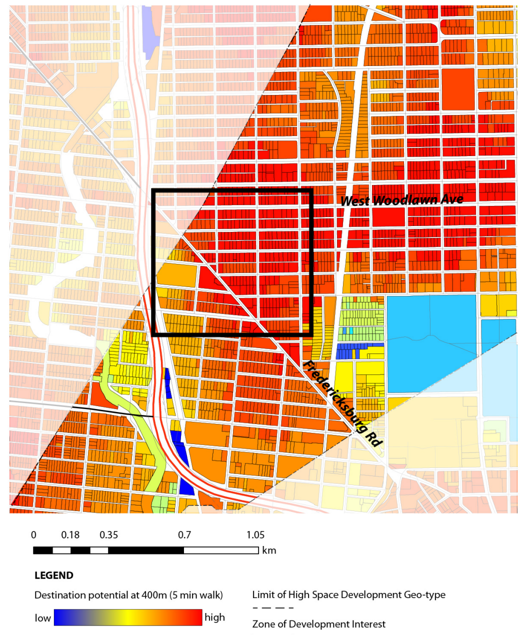


Figure 13. Fredericksburg Road and West Woodlawn Avenue

In general, VIA's comprehensive plan's proposed corridors coincide well with the regional radial movement network, linking major regional activity hubs, but their relationship to pedestrian-oriented areas becomes less certain particularly outside the downtown limits. Indeed, because the inner city is not situated over an area of high underground potential, there seem to be fewer opportunities for underground development to take advantage of San Antonio's existing pervasive centers. Extensive underground space use in the northern suburban sections of the Fredericksburg/Northwest and South/West Connector corridors may involve moving parking underground and increasing built density on the surface, but only in the short term. The many stops and stations proposed on the three corridors examined here could be opportunities to develop future centers. The metrics presented here would be able to aid in a future design process by testing the potential of outcomes.

The next steps in the case study of San Antonio will involve meetings with local experts, in order to better evaluate the development potential of the four underground resources and to discuss the results of the preliminary analyses of the urban fabric. Acquiring building footprints or more accurate georeferenced population or employment data would improve the analyses of the captive potential of land parcels or building footprints. A series of planning scenarios will be developed following these discussions and the evolution of the analytical methods. The scenarios will attempt to augment the form-based guidelines of the Downtown Design Guide currently being prepared by San Antonio's City Design Center (San Antonio City Design Center, 2014) through the analysis of other underground urban ensembles like the Montreal Interior City or the Tokyo underground. This catalogue of patterns presented three-dimensionally or in section will be validated in future case studies.

Towards volumetric city planning

This paper presented the recent progress in a methodological framework being developed by the Deep City project at the *École polytechnique fédérale de Lausanne* in Switzerland to investigate and evaluate the potential of underground resources in order to better inform urban planning objectives and scenarios. Contrary to the tradition by which the demand for underground resources precedes an investigation of resource potential, the project proposes a different approach by which planning scenarios emerge from coordinated surface-subsurface analyses. Using San Antonio, Texas, as an example, this paper demonstrated the benefits and a few limits of the data sources available and the generally complex nature of existing urban fabric. Indeed, the method is best applied to a real situation where the existing geological and urban conditions are less than ideal. The next steps in the analysis include questioning how form-based codes, used in San Antonio and elsewhere, may be a useful tool to move beyond traditional zoning and to bridge a gap between legal instruments like 3D cadasters and 3D property management and the issues to deal with in underground spatial configuration. This endeavor ultimately hopes to aid city planners, engineers and architects to better design and plan for and manage the limited underground resources of a three-dimensional, volumetric city.

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